A SYSTEM FOR THE SPECTRUM ANALYSIS
OF GEOMAGNETIC MICROPULSATIONS

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Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

1960

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from the

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ABSTRACT

This paper describes a system for the spectrum analysis of micro-
pulsations of the earth's magnetic field in the frequency range of .02
to 10 cycles per second.

The details of a method of recording, on magnetic tape, the frequency
modulated output signal of an optically pumped alkali vapor magnetometer
are given. This recording method incorporates a system for the cancel-
lation of the spurious frequency modulation of the recorded signal caused
by tape speed flutter introduced by the magnetic tape transport mechanism.
The spectrum analysis is accomplished by repeated high-speed playback of
the recorded signal through a tunable bandpass filter.

The author wishes to express his appreciation to Varian Associates,
Palo Alto, California, where the work described in this paper was accom-
plished, to Dr. Martin Packard and Mr. Kenneth Ruddock of Varian without
whose help the project would not have come to a successful completion,
and to Professor Carl E. Menneken of the U. S. Naval Postgraduate School
for his advice and encouragement.

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1. Introduction.

As long ago as 1861 fluctuations in the earth's magnetic field
were observed and reported upon. [1] Since that date geophysicists
and scientists in related fields have observed and recorded these vari-
ations which are known as geomagnetic pulsations.

The earth's magnetic field has a nominal value of 51,000 gammas[1]
in the neighborhood of 37° N. latitude on the West coast of the United
States and varies throughout the world from a high of 72,000 gammas to
a low of 25,000 gammas. (Both of these extreme values exist in the
Southern hemisphere.) See Fig. 1.

What might be considered the longest term field variation is the
annual change in the earth's magnetism. The magnetic field is increasing
annually at the rate of 160 gammas in some areas while it is decreasing
as much as 200 gammas per year in other regions. [2]

Probably the most widely known variation in the earth's magnetic
field is called the diurnal variation. It is caused by an action known
as the geomagnetic tide, a complex system of motions in the ionosphere,
involving changes in temperature and ionization due to the variable
access of solar energy, along with gravitational forces imposed by the
sun and the moon. This movement of conducting material, probably in
the E layer, generates electric currents that produce daily variations
of the earth's magnetic field of the order of 10 to 40 gammas in most
latitudes. [3]

These fluctuations vary greatly from day to day in amplitude and
detailed configuration, but for ordinary ("quiet") days they present in

[1]One gamma = 10^{-5} gauss
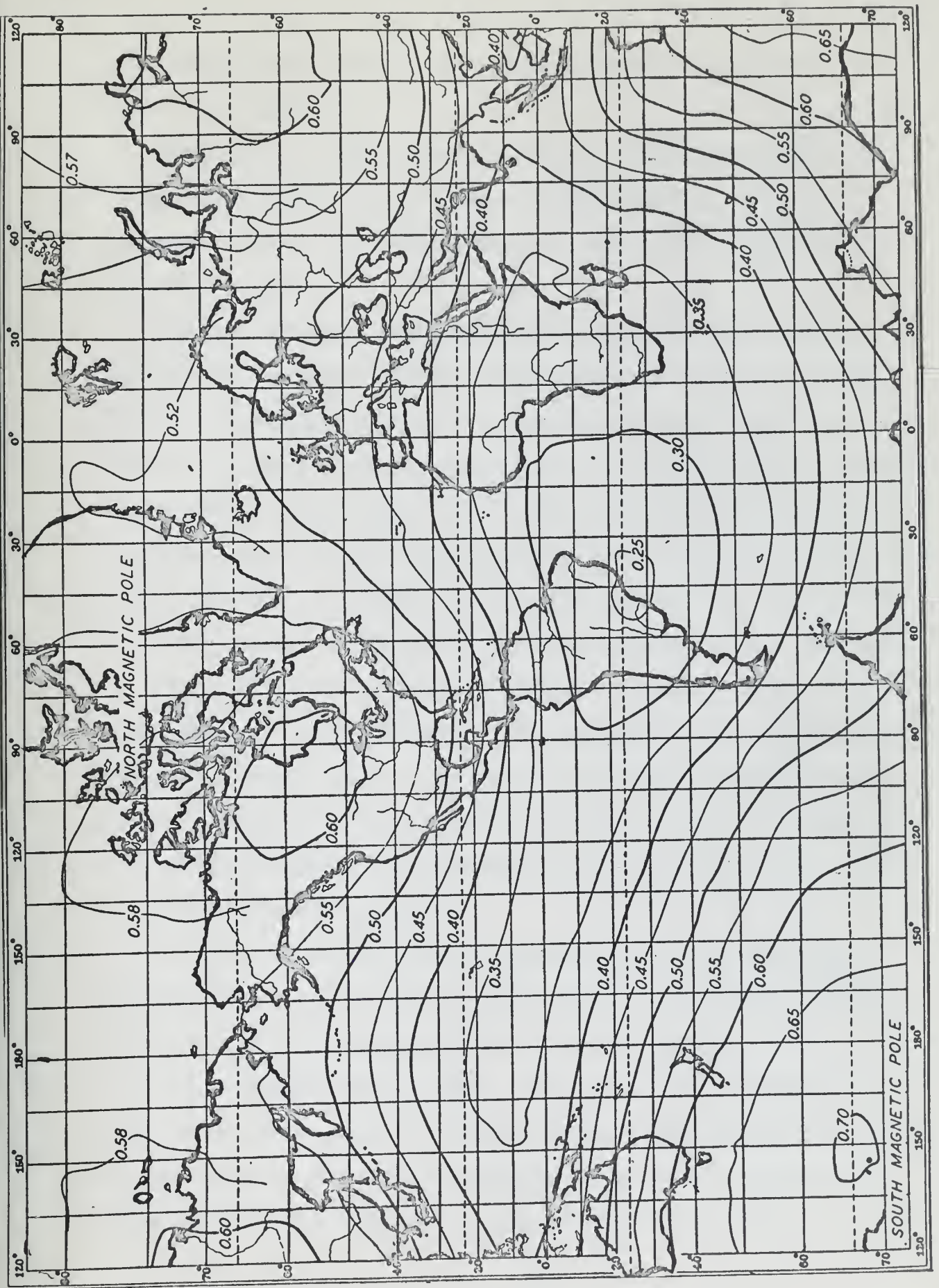
THE TOTAL INTENSITY OF THE EARTH'S MAGNETIC FIELD

Expressed in Oersted

Figure 1

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long-term averages a clear-cut pattern depending upon the season and the phase of the solar cycle.

Another fairly common feature of the earth's magnetic field may be observed when a particularly severe solar disturbance is acting. This phenomena, known as a magnetic storm, may contain field departures of 500 gammas or more.

Most storms begin suddenly and simultaneously over all the earth. These Sudden Commencement Magnetic Storms are characterized by a sudden change in the daily field variation expected on a normal day. This change consists of a sharp front, the first phase, in which the field is increased to the order of fifteen gammas in the first few minutes and then decays in several hours. A second phase follows in which the field is reduced by about 35 gammas in roughly 16 hours after the beginning of the storm. The field then recovers its normal day value only after several days. [4]

Generally the term pulsations as applied to geomagnetic phenomena is used to designate field fluctuations that have periods from a fraction of a second to several minutes. The pulsations usually have average amplitudes of a few gammas or less and so have become known as micropulsations. It is generally accepted that micropulsations occur in three types: Pc's, Pt's, and Giant micropulsations.

Pc's occur typically during the daylight hours. They are regular, long wave-trains of up to about one minute period with average amplitudes of one gamma or less and have a 27 day recurrence tendency. [5]

Pt's occur principally at night. They consist of well-damped longer period oscillations, usually of greater amplitude (by a factor of two or so) than the Pc's. Pt's are often accompanied by bay disturbances. [6] A magnetic bay is a well-defined rounded excursion of 50 gammas or so from

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an otherwise smooth course, completed in perhaps an hour.

The third type of pulsations is known as the Giant or Rolf micro-pulsation. They appear only in the auroral region and have amplitudes that may reach 40 gammas and periods as long as 150 seconds.

Since the end of World War II, interest in all of the physical characteristics of the earth has increased greatly. With the advent of this more universal thirst for geophysical knowledge, the emphasis on investigations such as that of the geomagnetic micropulsation phenomena has taken on new importance.

The purpose of this paper is to describe the design and operation of a low cost system that can be used in conjunction with a magnetometer, to analyze earth's field micropulsations as to amplitude and frequency spectrum distribution.

2. Choice of data source.

When first looking at the present "state of the art," a wide choice
of magnetic field sensing devices present themselves as possible data inputs
for the analysis system. It therefore seems advisable, at this point, to
set down a list of device characteristics that can be sought after as
ideally suited to the task of converting the actual field fluctuations to
some sort of usable signal.

First of all, it is obvious that the device that is the most sensitive
to magnetic fields and especially to field changes is the most natural
choice for the task at hand. Although it is a desirable characteristic,
it is not mandatory that the absolute value of the total field be measured.

Second: the accuracy of the proportionality between the output signal
and the input field change must be extremely high to allow for accurate
determination of the actual micropulsations.

Third: the signal to noise of the sensing element must be as high as
possible to preclude the possibility of false signal levels and frequencies
being introduced into the data by the sensing equipment itself.

Fourth: the necessity of long and involved equipment set up and
calibration procedures is considered objectionable.

Fifth: one of the high priority aims of the system design is that it
can be easily moved to various locations for geographically wide spread
field analysis. To this aim the sensing system must have small size,
fairly light weight, be mechanically rugged and be capable of rapid erec-
tion.

Sixth: a continuous data flow is not obligatory but a sampling type
data system may result in difficulties in analysis of the resulting piece
by piece information.

In light of this list of desirable characteristics, it should now be possible to review the instruments that have been used in the past for this kind of study and also to investigate the properties of some of the relatively new magnetic field sensing devices that might be used as signal sources.

Variometers

Historically, the first serious studies of micropulsations were accomplished with the aid of variometers. Variometers (typical of this class of instruments is the La Cour variometer) usually measure magnetic field in terms of three components, the horizontal intensity, the vertical intensity, and the declination (labeled H, Z, and D respectively). Each of these components is measured by the force of the magnetic field on a finely suspended magnet. Attached to the magnet is a small mirror by which a light beam can be reflected to record an accurate position of the magnet on photographic paper.

The variometer is primarily a magnetic observatory type of instrument. In light of the requirements of this project it suffers many deficiencies. This device is difficult to set up, requires a rigid platform and extensive calibration. Because of changes in strength of the sensing magnet with time and other degrading factors, the calibration must be repeated at intervals to ensure accuracy.

Probably the most important factor that prohibits the use of a variometer is that the amplitudes of short term micropulsations (with periods that are less than ten seconds) are greatly amplified through resonance effects of the variometer suspension. They are therefore recorded as changes of 100 gammas or more, when in actuality most of these relatively fast fluctuations have amplitudes of only a few gammas at most.

Search Coils

The sensing method used most extensively in recent studies of micro-pulsations is the detection of changes in the earth's magnetic field by use of large "search coils."

The usual search coil installation consists of from one to three large air cored coils whose diameters may range from two meters to about 20 feet. [4,7] Each coil senses the change in only one component of the field and so three orthognal coils are needed for detection of the complete signal. In some installations only one component will be measured by the installation of a single coil, or one or more of the air cored coils may be replaced by smaller mumetal cored solenoids. [7] The use of these solenoids results in loss of system signal to noise ratio due to Barkhausen noise in the core and loss in calibration stability resulting from core permeability changes caused by variation of the ambient temperature of the core.

The fluctuations in the magnetic field result in potentials being induced in the coils. These changing potentials are amplified and then recorded on paper by graphic recording galvanometers for subsequent analysis.

As a data source, the search coil method has many of the desirable features sought after for the analysis system under consideration. These coils will respond to field fluctuations over a wide range of frequencies. The highest frequency of usable response is limited by the natural resonant frequency of the coil, which is of the order of 150 cycles per second for a 20,000 turn coil of two meter diameter. [4] The lower frequency limit of these installations is usually determined by the amplifiers and recording equipment following the coils.

Another attractive feature of the search coil method is the high sensitivity to field changes. With coils of only moderate size, and reason-

able care in the design of associated equipment, sensitivities of the order of .01 gamma may be obtained.

Despite these desirable attributes, there are a number of other factors which preclude the use of search coils in the present analysis system. The large physical size of the search coils prevents them from being readily moved from one location to another. Because of their size, wind and other disturbances can produce mechanical vibration of the coils, resulting in the generation of voltage signals in a stationary field. These signals would, of course, have no relation to the desired micropulsation signals. To eliminate this difficulty the coils can be buried beneath the surface of the ground but this also decreases their portability.

The coil system also requires calibration since the size of the coil determines the amount of induced voltage produced by a given field fluctuation. This calibration should hold constant over a long period of time in one location but recalibration would have to follow each change in location.

As mentioned earlier, although it is not mandatory, a system that can measure the absolute value of the earth's magnetic field would be desirable. The search coil method does not have this facility.

Next to come under consideration is a large group of field sensing devices which have come into use in relatively recent years. It is convenient to class these magnetometers into two broad catagories which will be labeled the resonant and the nonresonant types.

Nonresonant magnetometers are those which employ some sort of magnetically sensitive element which obtains its measure of magnetic field by the proportionality between voltage or current in the sensor and the magnetic field along one axis of the sensor. Included in this group of devices are

the fluxgate or saturable core, the electron beam, and the Hall effect sensors.

Fluxgate

The fluxgate sensor makes use of the variation of permeability with intensity of magnetization in a ferromagnetic core. An easily saturable ferromagnetic core of high permeability such as supermalloy, mumetal, or permalloy, is driven cyclially into saturation by an applied magnetic field in the presence of a component of external magnetic force parallel to the axis of the core. The output emf has an asymetrical wave form containing both even and odd harmonics of the drving frequency.

When the external field decreases, the even harmonics, which cause the asymmetry, are suppressed and completely vanish for zero external field. Although the odd harmonics also vary with the magnitude of the external field, they do not vanish with zero field and they are not sensitive to the polarity of the field as are the even harmonics.

Two general types of even harmonic detection systems have been employed. In the balanced inductor magnetometer, two inductors are made geometrically parallel and are electrically connected so that the even frequency voltages add and the odd frequencies oppose in the detector. Either a single even harmonic term or all of the even harmonics may be used to indicate the magnetic field strength.

In a magnetometer where a single even harmonic is to be used, a single inductor can be employed. The inductor is excited through a band-pass filter designed to pass only the fundamental frequency of the driving oscillator. One of the even harmonics generated in the inductor is then fed to an amplifier and recorder through another narrow band-pass filter. With careful design of these circuits, a laboratory sensitivity of better

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than 0.1 gamma is possible.

Three mutually perpendicular inductors can be made to measure small field changes in terms of the scalar energy in the magnetic field. Such a system does not approach the required precision unless one of the three inductors is nearly parallel to the total field vector. For example, if the Field-parallel coil is two degrees off of the correct orientation, a correction of about 3° has to be made in the component measured by this inductor if the total error is to be kept below one gamma. [8]

In practical magnetometer systems using this type of sensor, small field suppressor coils are placed in the vicinity of the detector head. By passing a DC current through these coils, a magnetic field is set up that is in opposition to the earth's field. The suppression field strength is adjusted to approximately 5000 gammas below the earth's field. Since the output of the sensor is linearly proportional to this 5000 gamma residual field, as long as the suppression current remains constant, the changes in the output of the head are directly proportional to changes in the magnitude of the earth's field. [9]

The fluxgate magnetometer has the advantage of a very small sensitive area and a high sensitivity to field changes. The ultimate sensitivity is determined by the noise level of the sensing head. This head noise is caused by fluctuations in the domain boundaries in the sensor cores and by other related ferromagnetic effects and by variations in the suppressor coil current.

The major disadvantages of the fluxgate instrument are its need for precise orientation, the need for field compensating coils with very constant suppression currents and the extreme sensitivity of the sensing head to minor mechanical shocks.

Electron Beam

The electron beam magnetometer is based on the fact that a beam of electrons will be deflected by a magnetic field. The magnetometer consists of an electron gun, a long focus electrostatic lens and two overlapping collector plates that act as a detector. All of these elements are in an evacuated glass envelope.

Current flowing in bias coils located around the envelope produces magnetic fields which are used to exactly cancel the effect of the earth's ambient field. The electron gun and lens system is so designed that under this no-field condition, one-half of the image of the electron beam falls on each of the collector plates. When a change occurs in the earth's field, the electron beam is deflected and the difference in current flowing from the two collector plates is a measure of the magnitude of the field change.

The theoretical limit of sensitivity to field changes is 3×10^{-3} gamma. [10]

Because of the use of bias coils, all of the related problems of the fluxgate type instrument are also encountered in this unit including orientation sensitivity, noise from current variations in the bias coils and the need for calibration. In addition, highly stable power supplies are needed for the electron optics.

Hall Effect

The operation of the Hall effect magnetometer is based on the fact that if a sample of a semiconductor is placed in a magnetic field and if a current is made to flow through this sample in a direction perpendicular to the magnetic field, a voltage is produced across the sample along an axis normal to both the magnetic field and the direction of current flow. The

magnitude of the potential gradient thus established is proportional to the current density, the magnetic field strength and the majority carrier mobility in the semiconductor.

Any change in the magnetic field will produce a corresponding change in the voltage across the sample. If a semiconductor which possesses a high effective carrier mobility, such as indium antimonide, is used, direct measurement of very low fields is possible. To further increase the device's sensitivity, the earth's field can be concentrated onto the specimen by means of mumetal rods. In this way, the component of the earth's field can be magnified by a factor of a thousand or more.

By use of concentrating rods and a DC amplifier to magnify the voltage change produced across the sample, a signal equal to noise can be obtained for a field change of 0.1 gamma. [11]

This device may or may not be used with bias coils to place the sensing element in zero magnetic field. If the coils are used, the instrument is basically the same in operation as the fluxgate. If the coils are not used, calibration difficulties arise and the unit is extremely sensitive to temperature changes.

Unlike the devices previously described, resonant magnetometers measure the total magnetic field present in the area of the sensing element instead of just one vector component of the field. Due to this characteristic the fluctuations (noise) in line with the total earth field vector are observed when a single sensor of this type is utilized.

Since it is the micropulsations of the total earth's magnetic field that are of interest, this feature is one in favor of the choice of one of these instruments for the investigation under consideration.

At present writing there are three types of resonant magnetometers that

have been developed, the proton free precession magnetometer, the Overhauser proton magnetometer and the optical pumping magnetometer.

Proton Free Precession Magnetometer

The proton free precession magnetometer utilizes the principle of nuclear magnetic resonance to measure the absolute value of a magnetic field. These measurements are possible because the nucleus has an intrinsic magnetic movement and spin angular momentum and so will precess about a magnetic field at a frequency proportional to the field strength.

In the practical proton free precession magnetometer, some of the nuclei of a sample of water or a light hydrocarbon are aligned with a strong polarizing field created by a direct current flowing through a coil surrounding the sample. This field must have a component perpendicular to the magnetic field to be measured. When the polarizing field is suddenly shut off, the nuclear moment that has been left perpendicular to the earth's field will experience a force causing the protons to precess in phase about the earth's field. The frequency of precession is only dependent upon the magnetic field present and a nuclear constant, the gyromagnetic ratio for the nuclei of the sample used. The precessing moment induces a voltage in a pickup coil and the frequency of this voltage gives the magnitude of the earth's field.

The accuracy of the field measurement is independent of the orientation of the polarizing and pickup coils because the precession takes place about the total field, but the signal amplitude will fall off if the polarizing coil is not oriented perpendicular to the earth's field. Since the gyromagnetic ratio for protons in water has been measured to an absolute accuracy of 13 parts in one million, this

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constitutes the absolute accuracy of this device. The relative sensitivity is limited by the frequency measuring circuitry used in conjunction with the unit. In practice a relative sensitivity of approximately 0.1 gamma is obtainable in fields whose absolute strengths are approximately 50,000 gammas.

Because of finite time is needed to polarize the sample and due to the exponental decaying nature of the precession signal, a magnetometer using this phenomenon can not provide continuous data. As mentioned previously in the list of signal source characteristics, continuous data flow is not mandatory but is desirable.

Aside from this limitation the only other obvious drawback to the use of the proton free precession magnetometer as a system signal source is the limit on relative accuracy. If no other magnetometer could be found with relative sensitivity better than 0.1 gamma, the free precession magnetometer would have been chosen for the system but this is not the case.

Overhauser Proton Magnetometer

The Overhauser proton magnetometer is another application of nuclear magnetic resonance. This instrument employs a special proton sample containing a solution of peroxylamine disulfonate radical, $ON(SO_2)_3$. A strong rf field at about 55 megacycles is used to polarize the protons via the Overhauser effect. In this way, the need for separate polarizing and readout times is eliminated.

Thus the advantages of the proton free precession magnetometer are obtained along with a higher data rate.

The main disadvantage of this system is that the proton sample is not stable. It must be kept within a critical temperature range

and decomposition necessitates the periodic replenishment of the sample.
In light of the characteristics of the optically pumped magnetometer
to be described next, this drawback precluded the use of the Overhauser
proton magnetometer in the analysis system.

Optically Pumped Alkali Vapor Magnetometer

The development of the optically pumped alkali vapor magnetometer
was started at Varian Associates in the spring of 1958 following the
demonstration by Bell and Bloom [12] that an optically pumped alkali
vapor exhibited detectable field dependent resonance lines.

In the magnetometer utilizing rubidium vapor, light from a Rb
lamp is passed through an interference filter which passes the strong
Rb optical line at 7948A but not the one at 7800A. This light is
circularly polarized by a polaroid sheet and then passed through an
absorption cell containing Rb vapor and an inert buffer gas.

The simplified energy level diagram for rubidium 87, shown in
Figure 2, will aid in the description of the action that takes place
within the gas cell. (The line spacings on this diagram are not to
scale.) Only the quantum states involved in the pumping action are
shown in this diagram, since only the 7948 light passes through the
cell.

In a magnetic field the two hyperfine sub-states, F1 and F2, of
each of the principal energy states of the atom are split into 3 or
5 levels denoted by the letter m. The number attached to each m level
represents the orientation of the combined spin axes of the nucleus
and outer electron relative to the direction of an external magnetic
field when the electron occupies that particular level.
The separation of adjacent m levels in cycles per second is given by
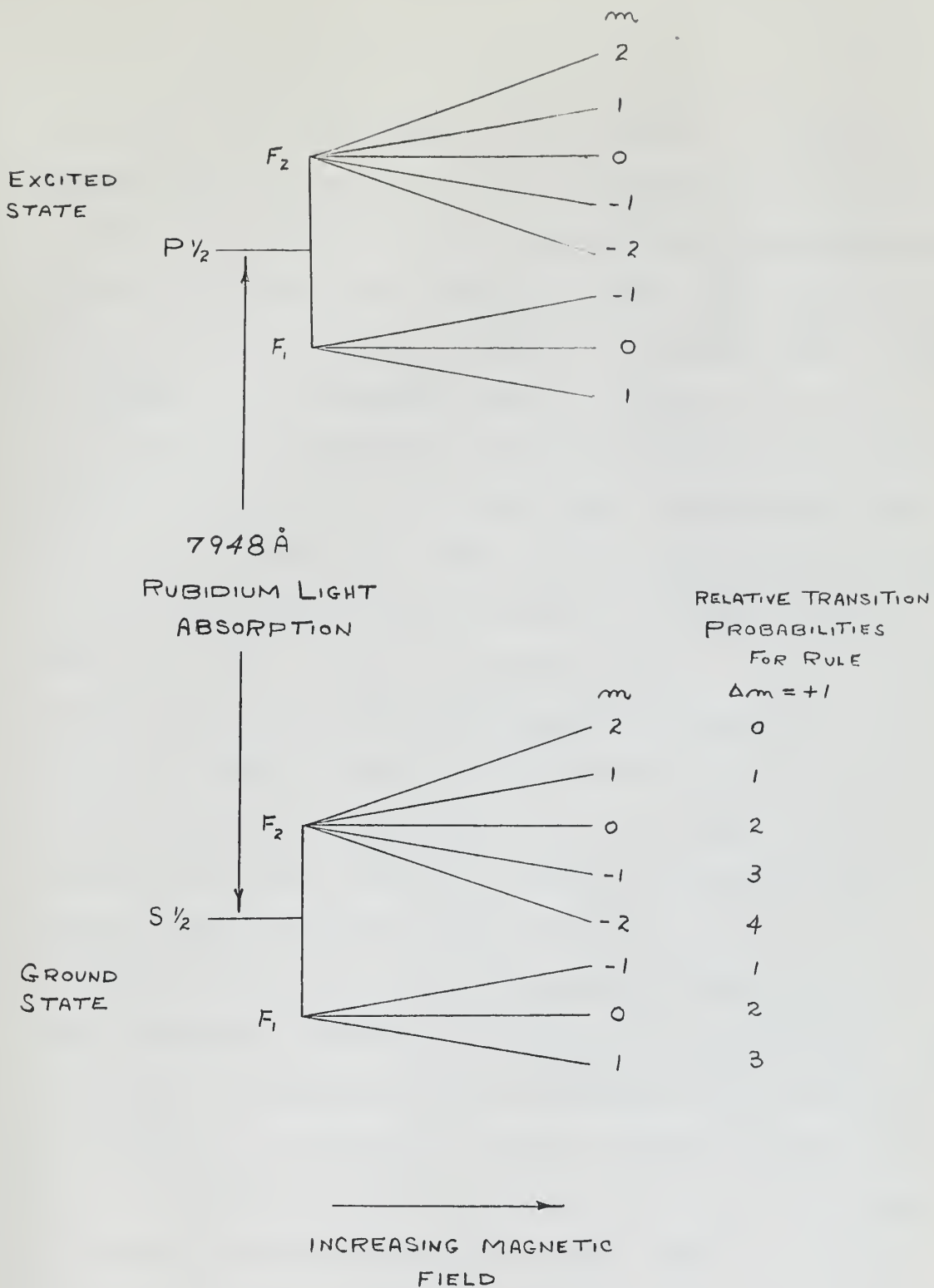
Rubidium 87 Energy Level Diagram

Figure 2

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$$f = 699{,}632 \ (H) \quad \text{for the rubidium 87 isotope}$$

where (H) is the external magnetic field in gauss. The optical
pumping technique provides the means for detecting this frequency.

When the circularly polarized 7948A light from the rubidium lamp
is passed into the gas cell, resonance absorption takes place in which
electrons in the ground state are raised to the excited state. However,
in a magnetic field the quantum selection rule that m must change by
+1 for the electron transition to take place prohibits electrons from
leaving the m = +2 level of the ground state. As the transition pro-
bability for all other ground state levels is large, most of the atoms
soon hold their valence electron in the M = +2 level of the ground
state and the vapor then has a net magnetic moment. The corresponding
selection rule for electrons dropping back to the ground state from
the excited state has no effect as the electrons in the excited state
are rapidly disoriented. The moment vector then starts to precess at
a frequency (the Larmor frequency), identical to the level separation
frequency, about the external magnetic field.

Each half cycle of precession is equivalent to changing the m
number, defined by orientation, and thus light is again absorbed. For
this process to continue such that the alternating light absorption
can be observed, it is necessary to provide a feedback magnetic field
which is oscillating at the Larmor frequency but is 90° out of phase
with respect to the detected oscillating light signal. To obtain a
measure of the magnetic field intensity present in the area of the gas
cell it is simply necessary to measure the resulting Larmor frequency
which is represented by the required feedback magnetic field frequency

A description of a practical magnetometer using this principle is

contained in the Appendix of this paper.

The present known accuracy of the constant which relates the magnetic field intensity and the Larmor frequency limits the absolute accuracy of the measurement of the earth's magnetic field with the rubidium vapor magnetometer to about two gammas. The relative sensitivity is limited only by the system self noise and the technique used to measure the output frequency.

Tests have been made comparing the output signals of two separate rubidium vapor magnetometers located at the Varian Associates plant in Palo Alto, California. The results of these tests show that a relative sensitivity of .002 gamma is obtainable with the present state of the art.

This type of magnetometer is very rugged mechanically as is evidenced by the fact that it is presently being used in rockets and satellites for space exploration.

The small size and ease of portability of the equipment, the ability to accurately measure the relative changes of the earth's field with such high sensitivity without critical orientation of the head or complicated calibration, and the continuous data flow all nominate this field sensing device as the one to be used for the analysis system signal source.

3. System design.

It was decided to limit the scope of the present design to the production of a system capable of analyzing the geomagnetic fluctuations whose frequencies lie between .02 and 10 cycles per second. This frequency range overlaps, on both ends. the frequencies previously investigated by other authors in this field and also includes the region around one cycle per second.

Little information is available about the one cycle per second region due to the extremely small amplitude of magnetic pulsations near this frequency. By making use of the high relative sensitivity of the alkali vapor magnetometer, the system should be capable of producing useful information in this "quiet zone."

Once an adequate signal source has been obtained, the problem becomes one of signal analysis. There are numerous ways to analyze a signal sample as to frequency and amplitude of its fundamental components.

One fairly straight forward but tedious method that has been widely used is the direct Fourier analysis of the graphically recorded data. By dividing the sample into many small increments and measuring the amplitude at each interval, the fundamental frequency components that go to make up the complex waveform can be obtained by evaluation of the well known Fourier integral:

$$C(\omega) = \int_{-\infty}^{\infty} g(t) \, e^{-j\omega t} dt$$

where $C(\omega)$ is the frequency spectrum

and $g(t)$ is the time function of the wave

Although there is no doubt that this approach would produce the desired power spectrum, this method requires a great deal of computation which only becomes practical when the services of a programer and a high speed computer are available.

In recent years the techniques of the field of information theory have been applied to problems of the type under discussion. It has been shown [13] that the power spectrum of a nonperiodic complex waveform can be obtained by first obtaining the autocorrelation function for the wave:

$$C(\gamma) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} X(t) \, X(t+\gamma) \, dt$$

where $X(t)$ is the value of the complex wave at some time

and $X(t+\gamma)$ is the value at a time interval γ later

and then computing the power spectrum by the evaluation of the Fourier transform of the autocorrelation function:

$$P(f) = \int_{-\infty}^{\infty} C(\gamma) \, e^{-j \, 2\pi f \gamma} \, d\gamma$$

Proponents of this method of analysis claim that it is superior to the Fourier analysis in that it will produce a more accurately defined spectrum of a nonperiodic wave. [13, 14]

Again the major drawback to this approach is the complexity of the equipment needed to perform the indicated mathematical computations. In the practical case, the autocorrelation function is readily obtained by a simple electronic multiplication of the signal at time t with the signal at some later time $t+\gamma$. The difficult process to

accomplish is the evaluation of the Fourier transform. To obtain the value of this integral, an electronic analog computer is required.

Since one of the goals of this system design is to produce a system that has a relative low construction cost, any method which would require a complex computer for its operation must be ruled out.

The remaining approach (and one of the oldest historically) is analysis by use of filter techniques. The use of a tunable bandpass filter to investigate the frequency components of the signal seems to be a straight forward solution to the problem, but it produces a few difficulties that may not be immediately obvious when first considering the approach.

First of all, since the frequencies in the range of interest (.02 to 10 cps) are so low, the use of the numerous available filters designed for signals in the audio range of frequencies is precluded. A special filter that is capable of going down to .02 cycles per second would have to be obtained or designed.

Second, if the signal is to be analyzed directly as it emanates from the magnetometer, a separate filter must be used for each frequency range in which the component of the signal is to be measured. If only one filter were to be used and tuned to investigate each band of interest in sequence, it would require an extremely long sampling time at each frequency setting of the filter to obtain a true statistical component value. This fact results from the nonperiodic nature of the field fluctuation signal.

Both of the above listed difficulties would be remedied if the magnetometer signal could be recorded in some manner so that the same

signal could be played back over and over and at a rate greater than that at which it was originally recorded. By playing back the same signal as many times as there are bands of interest, one tunable filter can be used to make a complete frequency analysis by setting it to a different band for each playback. By increasing the playback speed, not only is the time for each run shortened but the frequency of the signal will be multiplied by the speed up ratio.

Due to the resulting higher signal frequencies, the design of the bandpass filter becomes much more feasible. The higher frequencies allow the filter's electrical components to be of practical size and so reduces the transient induced ringing time for the filter to a tolerable value.

Since this method of investigation of nonperiodic signals has so many desirable features, the field analysis system was designed around this avenue of attack.

Once it was decided to record the signal, the obvious and probably the most inportant task to present itself first was the necessity of discovering some method of recording which would be convenient and which would reproduce the recorded signal exactly.

At first consideration it seemed desirable to produce a system that would be capable of reading the signal directly from the graphical strip recording produced by the recorder connected to the magnetometer. This feat could be accomplished by a flying spot scanner or similar device.

Although such a device would not be excessively complex electronically, a mechanical system that would assure accurate and perfectly constant recorder paper speed during readout by the scanner would be

extremely difficult to design and construct.

Next to be considered was a system to record the low frequency signals on magnetic tape utilizing a commercially available tape recorder. These extremely low frequency signals can not be recorded directly on tape due to the low frequency cut off limitations of normal tape equipment. To overcome this obstacle, a circuit was designed and build to "chop" the low frequencies at a 100 cycle per second rate. The resultant output of the circuit was a 100 cps square wave amplitude modulated by the low frequency signal.

It was soon discovered that commercially available magnetic tape has such large nonuniformities in oxide coating thickness that the amplitude noise induced in the system due to the nonuniformities was of the same order of magnitude as the signal to be analyzed. Thus, recording of amplitude modulated signals had to be ruled out.

An investigation of the circuitry of the alkali vapor magnetometer reveals the fact that the basic signal output of the sensing head is a frequency modulated signal. Magnetic tape recording this FM signal would eliminate the noise difficulty resulting from tape coating nonuniformities.

Since the head output signal is approximately 238 Kc (in a field of 51000 gammas), the signal must be beat in a mixer against a local oscillator to produce a signal within the recording range of the tape equipment.

The most important limiting factor encountered in recording FM information on magnetic tape was the consistency of tape speed across the recording and playback heads. Any fluctuation in tape speed would result in additional frequency modulation of the signal which then

appeared as noise in the FM detector output.

If the signal consists of a large frequency deviation compared to the carrier frequency, the FM produced by the wow (long term speed variation) and flutter (short term or fast speed variation) introduced by the tape advance mechanism may be small enough to be of no importance. Unfortunately, in the case of the magnetometer signal, very small deviations due to the low frequencies of interest are of major importance.

A survey of commercial tape recording equipment revealed that a value of 0.1 for flutter can be expected even with the best units available. This means that a FM deviation of 0.1 of the carrier frequency is induced on the signal when a steady note is recorded or played back.

If the magnetometer signals were beat down to a carrier frequency of 1000 cps, this flutter would produce, on a record-playback cycle, an unwanted frequency deviation of two cycles per second or about 0.4 gamma of noise in magnetic field strength measurement. (one gamma = 4 2/3 cps when using Rb^{85})

If the data were to be recovered exactly after a record-playback cycle, some method of eliminating the FM due to the flutter had to be devised.

In order to accomplish this, the following system was developed. A tape deck equiped for recording two channels at once on 1/4 inch magnetic tape was utilized. The signal output of the magnetometer, after being beaten down to the low audio frequency range, was recorded on one channel (channel no. 1). Simultaneously, a steady audio tone of a frequency slightly higher than that of the signal on channel no. 1

was recorded on the other channel (channel no. 2).

Since the frequencies on both channels were approximately the same and they were both recorded and played back at the same time, the wow and flutter would produce the same frequency modulation noise on both signals. And most important of all, these noise signals would be coherent.

If each channel's output were demodulated separately and the resulting signals were used as the inputs to a different circuit, the flutter induced FM would be subtracted out, leaving only the low frequency magnetometer signal ready to be analysed. Figure 3 is a block diagram of this system.

As is indicated in Figure 3, two Hewlett-Packard HP 500B frequency meters were used as the FM demodulators for the system. These units are rate meter type devices. Figure 4 shows a simplified block diagram of the HP 500B.

An incoming sine wave signal is amplified and the positive crossings of the zero axis are used to actuate a Schmitt trigger circuit. The trigger circuit thus produces a pulse for each cycle of the incoming signal. Each pulse then is used to trigger a bi-stable multivibrator into its "high state." Simultaneously with the switching of the multivibrator a phantastron circuit is actuated and starts its rundown. When the rundown has reached a predetermined value, the multivibrator is switched back to its low state.

On each frequency range the time in the high state per input signal cycle is changed by changing the capacitor and resistor values in the phantastron circuit. This time is adjusted so that the pulses formed by the multivibrator changing states, when averaged by a built in filter,
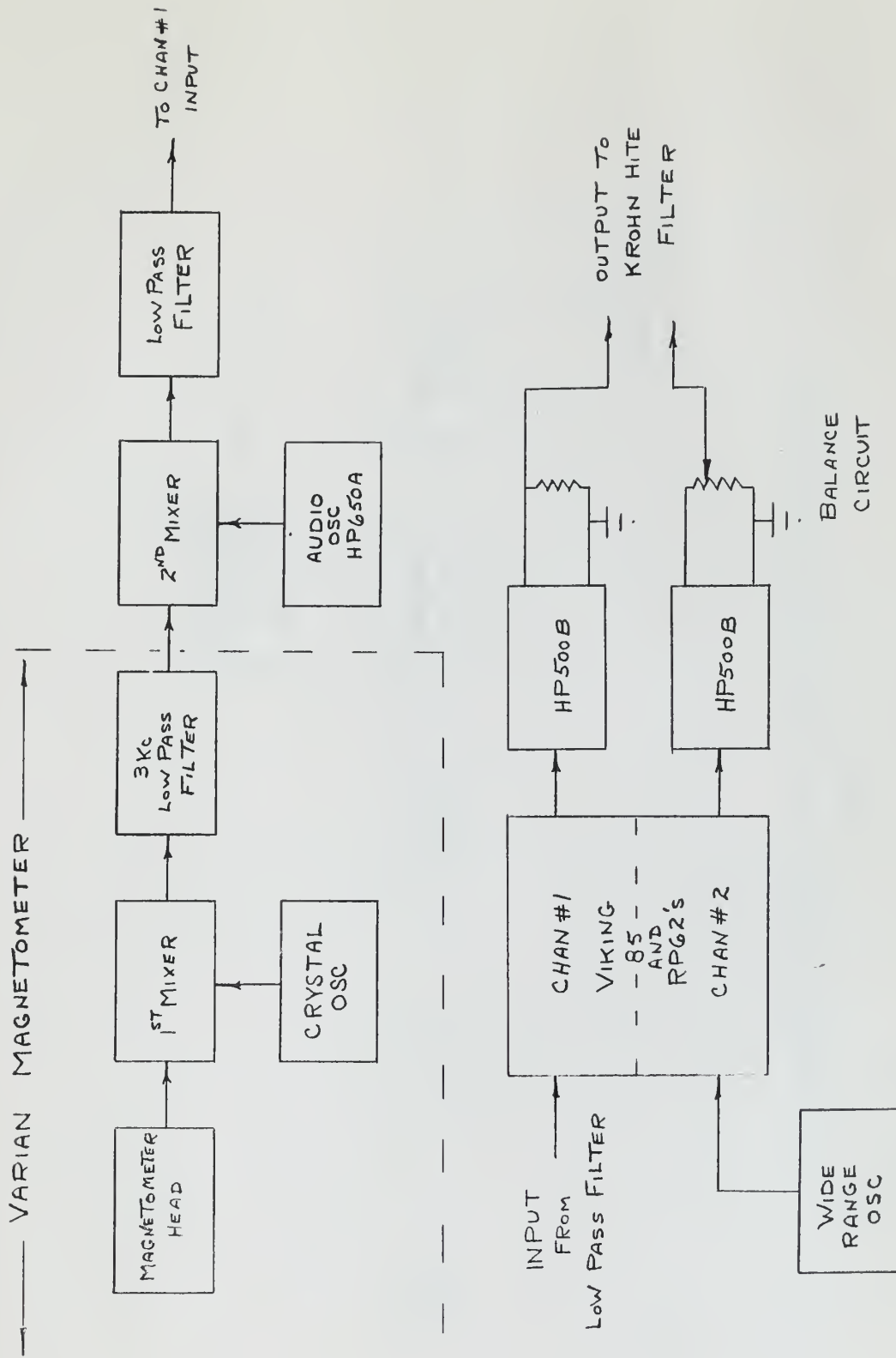
Block Diagram of Magnetometer Signal Tape Recording and Playback System

Figure 3
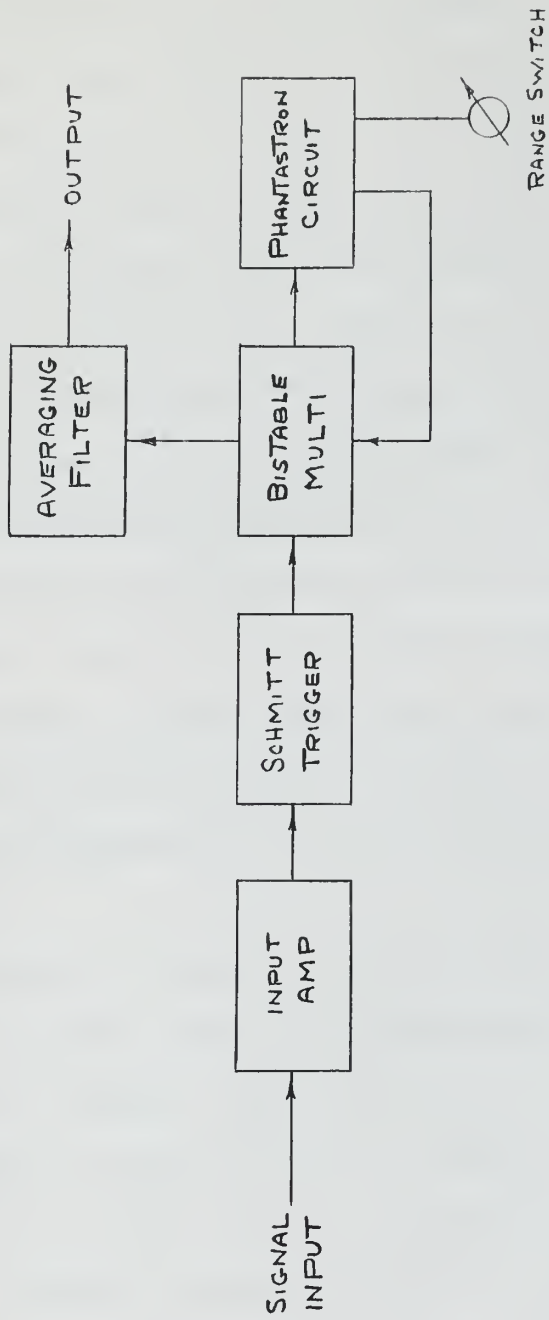
Block Diagram of Hewlett-Packard Model 500B Frequency Meter

Figure 4

will produce a full scale deflection of the indicating meter when a signal corresponding to the maximum frequency limit of the selected range is fed into the unit.

This full scale deflection also corresponds to a current of one milliamp flowing through a 1340 ohm resistor placed across the "recorder output" jack of the unit.

The HP 500B also contains a X3 and a X10 scale expansion setting. In these positions the sensitivity of the instrument is increased by 3 or 10 respectively. This function, with the aid of an offset control, takes any 1/3 or 1/10 portion of the frequency range selected by the range switch and expands it to the full range of the indicating meter. For example, by this means any 1000 cps or 300 cps portion of the 3000 cycle per second range can be adjusted to give from 0 to 1.34 volts across a 1340 ohm resistor across the recorder output jack.

The final result is a DC voltage output which is directly pro-portional to the frequency of the incoming signal. Therefore, any FM of the input signal appears as a variation in the level of the DC output voltage.

For the purpose of obtaining a two gamma full scale sensitivity on the basic magnetometer recorder, the HB 500B's had to be set on the 3000 cps range and the expansion control set on the X10 position. With these settings a frequency shift of one cycle of the input signal results in a change of 4.46 millivolts in the DC output level.

When the range and expansion controls are set at these positions and the built-in pulse averaging filter is used, the DC output voltage can accurately follow input modulation frequencies up to 8.9 cycles per second. By using an external filter, the units can be adapted to respond

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to modulation frequencies in excess of 5000 cps.

The difference circuit used simply consisted of two resistors, one of which was a variable Helipot control. The output of the channel no. 1 HP 500B appeared across the fixed resistor while the Helipot was used inconjunction with the HP 500B associated with channel no. 2. By varying the setting of the potentiometer, the amount of flutter cancelling signal could be controlled. The difference of the two outputs was obtained by taking the signal between the high sides of the two resistors. Since this produced a double ended signal (both leads floating above ground), the inclusion of a circuit to convert the double ended signal into a single ended one was considered. Because a circuit to accomplish this would of necessity included some active element, it was feared that this unit might contribute noise or low frequency drift to the signal. The final decision was to leave the signal double ended and to isolate all of the following equipment from the system ground.

Because of the low frequency nature of the wanted signal and due to careful attention to stray pickup, 60 cycle hum did not deteriorate the system response even though much of the equipment was above electrical ground.

Many record-playback test runs were made to determine the system's ability to reproduce the original low frequency information. The results of one of these tests are shown in Figure 5. The upper set of waveforms shows the original signal as it came directly from the magnetometer and the playback of the tape recorded signal without any flutter cancellation. The lower set of waveforms shows the original signal and the tape recorded playback with cancellation. (A close examination of the flutter-corrected playback signal will reveal larger amplitude
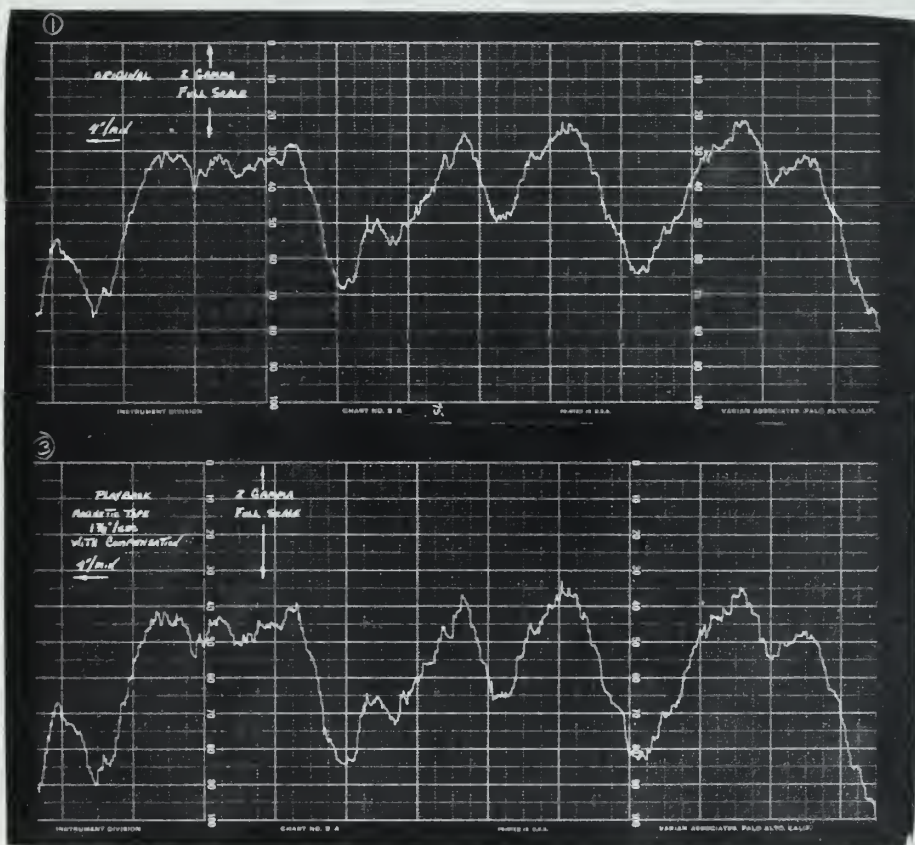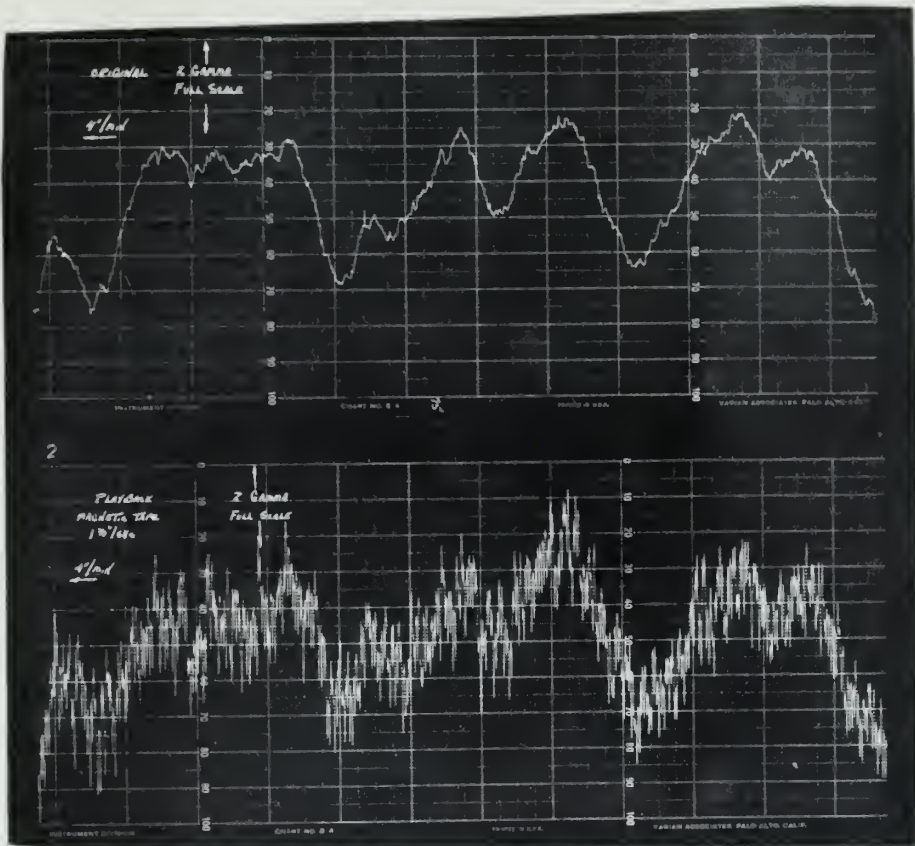
Graphic Results of Flutter Cancellation
Figure 5

excursions than that of the original signal. This system deficiency was present when these pictures were made but was corrected soon thereafter by the change of value of one of the resistors in the balance circuit)

Due to the frequency of the crystal available for use in the local oscillator of the magnetometer, the output frequency from the magneto-meter mixer was approximately 1000 cps for the fields encountered in the area where this system was constructed (Palo Alto, California).

It was decided to lower this frequency to about 250 cycles per second. Two reasons prompted this decision. First: the FM error produced by the tape speed flutter is a percentage of the recorded frequency, the lower this frequency the less error is introduced if the balance circuit isn't set to exact flutter cancellation. Second: subsequent plans call for very high speed playback of the recorded data. The lower the frequency of the carrier is made, the higher is the speed up ratio that can be used without obtaining a resulting signal which is above the normal audio range of frequencies.

To accomplish this transposition of frequency, a second mixer (with cathode follower) was constructed. A Hewlett-Packard model 650A test oscillator was used as the second local oscillator and the low pass section of an Allison Labs variable L.C. and H.C. filter allowed only the desired low frequency difference signal to pass on to the tape recorder. The equipment is shown in Figure 6.

Test runs made on the HP 650A when it was set at 800 cps (the second local oscillator frequency) showed its frequency to be constant to within a fraction of a cycle for a long time period. Since the crystal oscillator used with the first mixer drifted more than one cycle in the same time interval, the drift error contributed by the second mixer-local

Second Mixer and Associated Equipment

Figure 6

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oscillator equipment was considered to be negligible.

Once the recording system had shown satisfactory reproduction, the next logical step was to obtain a bandpass filter that would meet the required specifications.

Since the data was recorded at 1 7/8 inches per second and the maximum playback speed available on the Viking 85 tape deck was 7 1/2 inches per second, a speed up ration of four could be attained. The resulting frequency shift due to this speed up would require a filter that could tune from .08 to 40 cps to cover the original range of from .02 to 10 cps.

A Krohn Hite model 330A bandpass filter was made available for use in this system. This filter consists of a four section R-C low pass filter, a four section high pass filter and associated amplifiers to produce unity gain (0 db $\pm$ 1 db) in the pass band. The low and high pass filters are each independently tunable from .02 to 2000 cps. Out-side the pass band the attenuation is 24 db per octave with the maximum attenuation greater than 80 db.

The transfer function of the filter is approximately:

$$\frac{\omega^4 T_1^4}{\left[\left(1+2_j A\omega T_1 - \omega^2 T_1^2\right)^2\right]\left[\left(1+2_j A\omega T_2 - \omega^2 T_2^2\right)^2\right]}$$

where the low cut-off frequency is $\frac{1}{2\pi T_1}$ and the high cut-off frequency is $\frac{1}{2\pi T_2}$. The value of the peaking factor, "A", which is normally unity for filters composed of independent resistance-capacity sections, is fixed in this filter at slightly greater than 0.6. This value pro-duces less than 1 db peaks in the gain vs. frequency plot, but reduces the attenuation at the corner frequencies by approximately 8 db, and

permits a band width as narrow as one octave with very little attenuation in the center of the pass band.

The frequency calibration accuracy of this unit is $\pm$ 5% and in the configuration used, the internal generated noise is less than 100 microvolts.

In this sytem the signal input to the filter was at a relatively low value (a few millivolts) and since only signal components that fell into the pass band of the filter appeared at the output, an amplifier had to be included between the filter and the graphic recording equipment to increase the amplitude of the signals to a level great enough to drive the recorder

The amplifier used was a Video Instruments Co. unit. This transistorized amplifier has a maximum gain of 500 and has a flat response from DC to 250 Kc.

The graphic recording equipment consisted of a Sanborn DC amplifier and model 151 recorder. This instrument is capable of recording input signals up to 100 cycles per second. A paper speed of 1mm/sec was used on all analysis runs.

The completed system is shown assembled in the left hand relay rack in Figure 7. The right hand relay rack contains all of the electronic components of the magnetometer exclusive of those contained in the sensing head. Reading from top to bottom the equipment mounted on the left hand rack is:

Record-playback amplifier for channel no. 2
    (Viking RP62)

Viking 85 tape deck

Record-playback amplifier for channel no. 1
    (Viking RP62VU)

Balance circuit and system patch panel

Krohn Hite band pass filter Model 330A

Hewlett-Packard frequency meter Model HP 500B

Lambda DC power supply-for 2nd mixer

Beckman/Shasta Wide Range oscillator Model 301A
(channel no. 2 reference signal)

Isolation and line voltage regulation transformer
(Solar)

Not shown in Figure 7 is the equipment used to beat the magnetometer signal output down to the low recording frequency, which is shown in Figure 6. Also absent from the photograph are the Video Instruments Co. DC amplifier, the Sanborn amplifier and the model 151 recorder (not pictured in this paper).
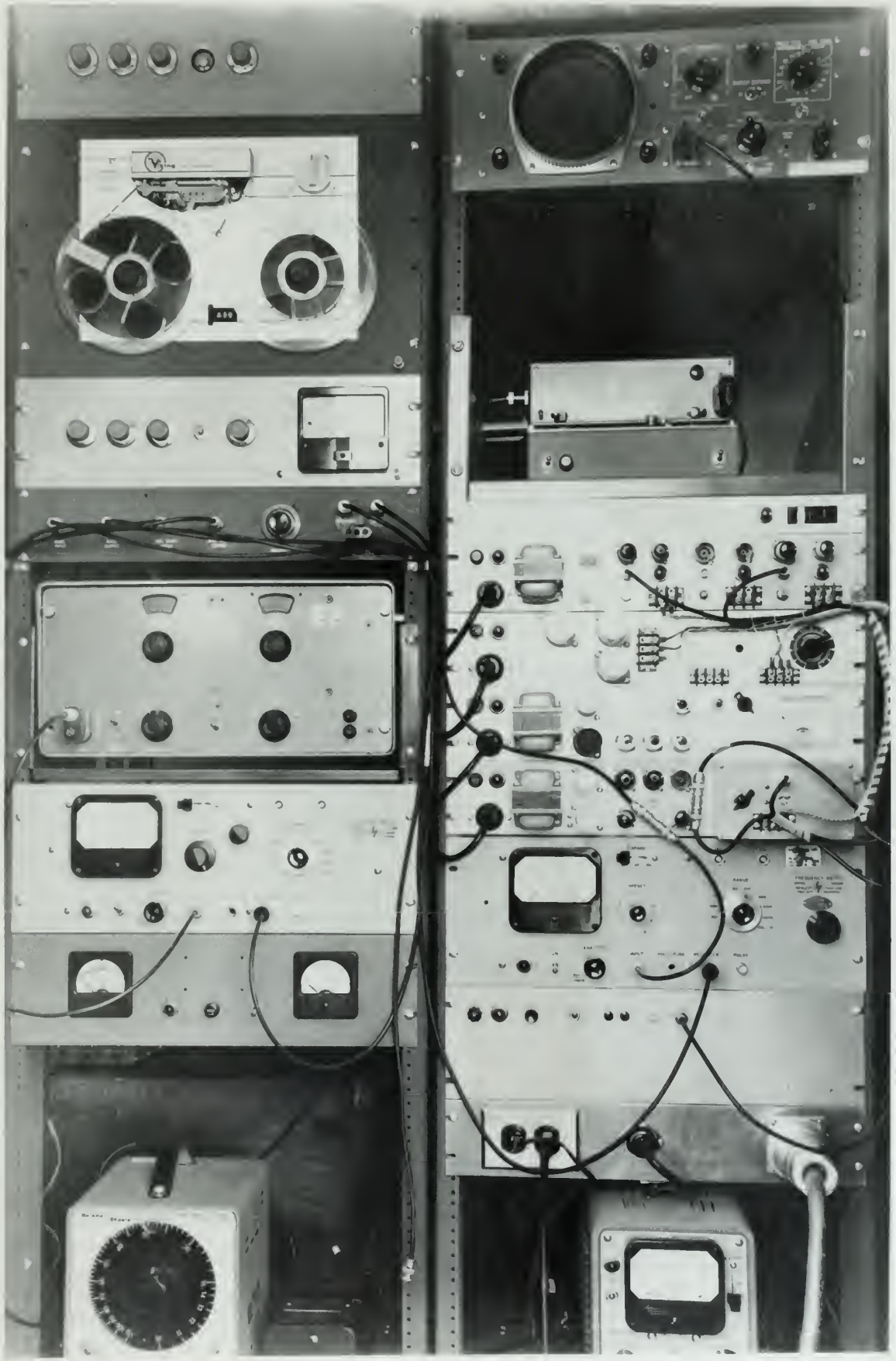
Analysis System and Magnetometer Equipment

Figure 7

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4. Results.

A sample recording of the earth's magnetic field was made on
5 March 1960 between 0620 and 0850. The Viking 85 tape deck recording
speed was one and 7/8 inches per second. The channel no. 2 signal,
emanating from the Beckman/Shasta Wide Band Oscillator model 301A, was
set at exactly 275 cps (as measured by a Hewlett-Packard model 524A
frequency counter). The second local oscillator was set so that the
resulting channel no. 1 signal carrier frequency was nominally at 250
cps.

On playback the Viking 85 deck ran at 7 1/2 inches per second. The
actual tape speed-up ratio of 3.8 was determined by measuring the re-
sulting channel no. 2 frequency and comparing it with the original 275
cps.

The flutter cancellation circuit was adjusted to produce the most
faithful reproduction of the original magnetometer signal. This was
accomplished by visually comparing the original magnetometer record
with the output of the playback system as recorded on the same Varian
G-10 graphical recorder that was used to record the original signal.
After the setting for the best reproduction had been determined an oc-
tave band analysis was made for the six octave frequency ranges lying
between .02 and 1.28 cps. (The filter settings ranged from .076 to 4.86
cps due to the 3.8 speed-up ratio.)

Normally the output signal of the magnetometer is recorded on a
wide paper chart by use of a G-10 recorder. The Sanborn recorder,
which was used in the octave band runs, utilizes a much narrower chart
and a different chart speed. Comparison of the original signal and the
band by band data was therefore quite difficult. To eliminate this pro-
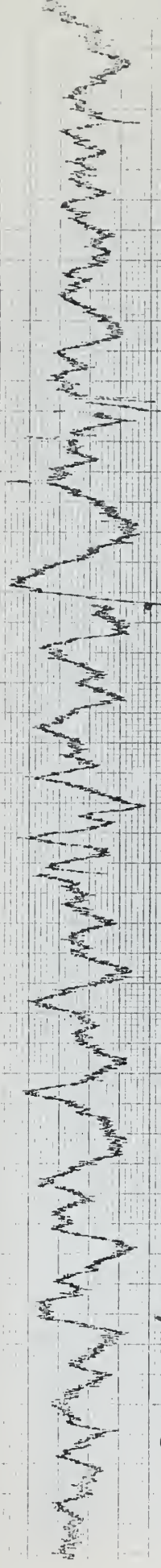
blem, a playback run was made with the Krohn Hite filter set at a wide pass band (.05 to 10 cps corresponding to .013 to 2.63 cps of the original signal) to provide a graphic record of the original signal on the same recorder that was used for the band analysis runs.

Small portions of these strip charts are shown in Figs. 8, 9 and 10. Note that the full scale sensitivity of the octave band signals was twice that of the original signal plot. The effective speed listed on these charts is defined as the actual chart speed (one mm/sec.) times the tape recorder playback speed-up ratio (3.8 in this case).

Referring to these plots, it can be seen that the results obtained correlate with those of other authors [4, 15] in that the earth's magnetic field fluctuations do occur in a burst or beat type pattern.

The presence of noise of the order of .03 gamma in the .64 to 1.28 cps band, where very little noise has been reported [4], indicates that the magnetometer location, Figure 11, was too close to power lines and other local sources of man-made noise. To obtain an accurate measure of the true micropulsation spectrum, the magnetometer will have to be moved to a remote area.
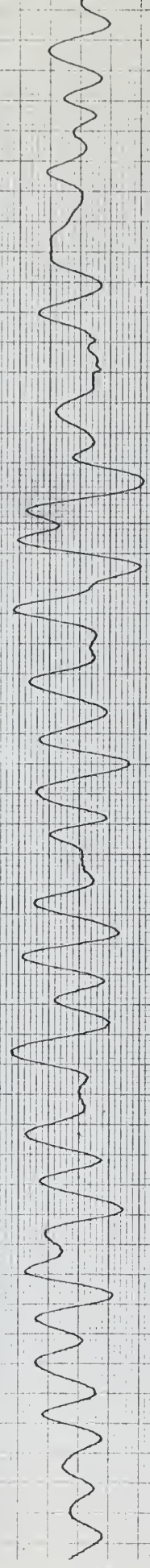
Graphic Results of Spectrum Analysis Run   Figure 8

Graphic Results of Spectrum Analysis Run

Figure 9

Graphic Results of Spectrum Analysis Run

Figure 10

Magnetometer Location

Figure 11

5. Future applications.

The apparent absence of a universally accepted theory to explain the cause of geomagnetic micropulsations points up the lack of sufficient information about this phenomena to test the various models that have been proposed. It is believed that a world wide network of magnetic observatories, all utilizing equipment similar to the optically pumped alkali vapor magnetometer, should be erected to correct this situation.

With such a network of stations, each with the capability of recording its data in some manner similar to that described in this paper, time synchronized world wide high sensitivity micropulsation measurements could be made. The resulting recordings could then be sent to a central location for high-speed analysis.

By collecting data in this way, information could be obtained on the propagation and the geographical extent of micropulsations and the large disturbances that are encountered daily in the earth's field. The availability of this data would permit an evaluation of all the proposed micropulsation theories.

One of the major advantages of having a centrally located data analyzing facility lies in the fact that only the simplest tape recording equipment need be installed at each observatory. The relatively expensive high-speed playback unit and band pass filters would be located at the central facility.

Of course, if such an extensive program was to be activated, a number of refinements would have to be made on the analysis system.

First: A slower tape speed and larger tape reels are needed to permit extended periods of continuous recording of the field.

Second: A higher speed up ratio is desirable to allow the analysis

runs to be made in a shorter period of time. A ratio of 100 to 1 could be used without obtaining carrier frequencies above the normal audio range if the magnetometer signal were beat down to about 100 cps.

Third: A system designed to keep the flutter cancellation signal at the correct value despite changes in the field signal carrier is required. Due to the fairly large diurnal variation of the earth's magnetic field, the carrier frequency would shift considerably during an extended recording run and flutter cancellation would rapidly deteriorate if an automatic control were not incorporated.

With the inclusion of these improvements, a workable and highly versatile magnetometer data analyzing system would result.

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APPENDIX

OPTICALLY PUMPED RUBIDIUM VAPOR MAGNETOMETER

The basic physical phenomena utilized in the rubidium vapor magnetometer, optical pumping, Zeeman Splitting and atomic precession, were discussed in the main body of this paper when this field sensing device was reviewed as a possible analysis system data source. The purpose of this appendix is to describe the engineering details of the working instrument.

Figure 12 shows an exploded view of the sensing head of the Varian Associates rubidium vapor magnetometer. Proceeding from right to left across the top of the photograph, first encountered is the transistorized feed back amplifier. This unit has essentially zero phase shift over its operating range. Immediately to the right of the amplifier is a rubidium spectral lamp. This unit consists of an RF oscillator at approximately 100 mc. which produces an electrodeless discharge in a 1/2 inch diameter bulb containing rubidium vapor.

The heat generated in the lamp unit maintains the lamp bulb at its proper operating temperature and aids in keeping the rubidium gas cell at about 40° C.

The light from the lamp travels to the right passing through the 7948A filter, a lens and a circular polarizer. Following the polarizer is the gas cell. The cell contains rubidium 85 at a pressure of about 10^{-6} millimeters of mercury and a buffer gas, usually neon, at about three centimeters of mercury.

The buffer gas is included to prevent the atoms from diffusing to the cell wall too rapidly. This keeps the rubidium atoms in the useful space of the cell for long periods of time providing long relaxation

Exploded View of Rubidium Vapor Magnetometer Sensing Head
Figure 12

times and consequently the narrow line widths that lead to high sensitivity to magnetic field changes.

Rubidium was chosen from among the various alkali metals because of its operating temperature of about 40° C. Other alkali metals require either higher or lower temperatures which would not be easily realizable in practical operation. Rubidium 85 was chosen over rubidium 87 because line width broadening effects are minimized in this isotope. By operating with Rb^{85}, an intrinsic line width of about 60 cps is obtained. This line width is broadened to about 120 cps by the incident light from the lamp.

After passing through the gas cell the light encounters another lens which focuses it on the photocell pickup. The photocell is a mosaic of silicon solar batteries. Although the response of a single silicon cell to high frequencies is low, the needed sensitivity is obtained by use of nine of these units in the makeup of the mosaic structure.

The intensity modulation of the light beam reaching the photocell corresponds to the Larmor frequency of the gas cell energy transitions. This modulation is converted into an AC voltage by the photocell and is passed on to the feedback amplifier. The amplifier then drives the RF feedback coils which surround the gas cell. These coils are shown directly below the gas cell in Figure 12.

A diagram of the packaged sensing head is shown in Figure 13.

The Larmor frequency for Rb^{85} is 467 Kc per gauss. The output of the photocell at this frequency is almost exactly the same as that of a tuned circuit whose Q is determined by the line width and whose center frequency is the Larmor frequency.

An exact analogy can be drawn between an oscillator whose frequency
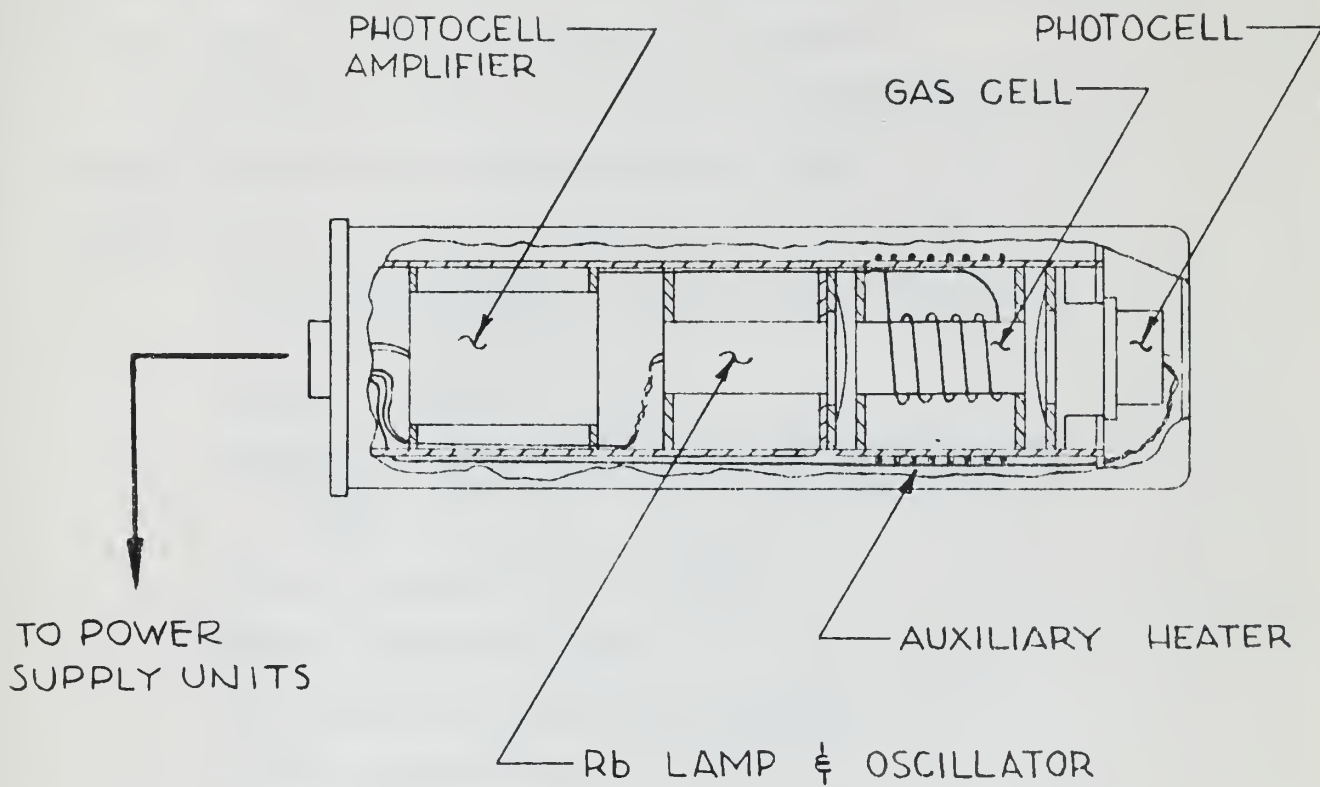
Assembled Rubidium Vapor Magnetometer Sensing Head

Figure 13

determining element is the combination consisting of the optically pumped system together with the photocell to detect the light modulation. By use of the amplifier and the feedback coils, a self socillator at the Larmor frequency is produced in the magnetometer.

In the self oscillator, a rapid change in field will result in a rapid change of instantaneous Larmor frequency which will be faithfully followed by the self oscillator output frequency as long as the spectrum of this output is within the bandpass of the amplifier.

The remaining equipment that completes the magnetometer unit is housed in the right hand relay rack shown in Figure 7. From top to bottom of this rack, these units are:

> HP 120A oscilliscope (for observing output signal
>   from sensing head)
>
> Varian G-10 graphic recorder
>
> Temperature regulator (for control of temperature of
>   sensing head and 1st local oscillator crystal
>   oven)
>
> Transistor amplifier power supply
>
> Spectral lamp power supply
>
> First mixer and crystal local oscillator
>
> HP 500B frequency meter
>
> Recorder DC bias control (for G-10 recorder)
>
> AC power and head cable connector panel

The sensing head output frequency is approximately 240 Kc when the unit is operated in the northern California region. This signal is beat against a crystal oscillator signal at 239 Kc in the first mixer and the resulting 1 Kc signal is fed into the HP 500B.
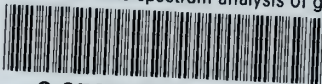
The output voltage from the HP 500B is recorded by the Varian G-10 graphic recorder. The recorder, whose sensitivity is set at 41.7 milli-

volts for full scale deflection, is kept on scale by application of a DC bias voltage from the recorder DC bias control.

For normal station magnetometer use, the instrument is run at 2 gammas for full scale deflection of the G-10 recorder.